PRECIPITATION CHANGE AND SOIL LEACHING: FIELD RESULTS AND SIMULATIONS FROM WALKER BRANCH WATERSHED, TENNESSEE

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Abstract. To investigate the potential effects of changing precipitation on a deciduous forest ecosystem, an experiment was established on Walker Branch Watershed, Tennessee that modified the amount of throughfall at -33 %, ambient (no change), and +33 % using a system of rain gutters and sprinklers. We hypothesized that the drier treatments would cause: 1) disproportionate changes in soil water flux, 2) increased total ionic concentrations in soil solution that would in turn cause 3) decreased SO_4^{2-}/Cl^- ratios, 4) decreased HCO_3^- concentrations, and 5) increased ratios of Al to (Ca^{2+} + Mg^{2+}) and of (Ca^{2+} + Mg^{2+}) to K^+. Hypothesis 1 was supported by simulation results. Hypotheses 2 and 3 were supported in part by field results, although interpretation of these was complicated by pre-treatment biases. Hypotheses 4 and 5 were not supported by the field results. Comparisons of field data and Nutrient Cycling Model (NuCM) simulations were favorable for most ions except Cl^- and K^+. The disparities may be due to underestimation of soil buffering in the case of Cl^- and overestimation of soil buffering in the case of K^+ in the model. Long-term simulations with NuCM suggest that reducing water inputs will slow the rate of soil acidification and P loss, but will not materially affect growth or ecosystem N status.

Keywords: leaching, Nutrient Cycling Model, rainfall, soil solution chemistry, Walker Branch Watershed

1. Introduction

Climate change could affect the cycling of nutrients and productivity of forest ecosystems in a number of ways. To date, most studies have emphasized the effects of temperature or elevated CO_2, but changes in precipitation may have equal or greater effects (Kirshbaum et *al.*, 1992; Melillo *et al.*, 1996). Specifically, changes in precipitation could cause: 1) changes in productivity in water-limited ecosystems, 2) changes in water yield, and 3) changes in water quality and soil leaching rates. In the Solling forest ecosystem in Germany, Ulrich (1983) noted pulses of NO_3^- and Al during warm, dry years. He hypothesized that drought intensifies N mineralization and nitrification during summer, resulting in NO_3^- pulses during re-wetting periods. In acidic soils, the NO_3^- pulse is accompanied by a pulse in soil solution Al concentrations. Lamersdorf *et al.* (1994) describe a field research project designed to test Ulrich's hypothesis on a large scale. The Experimental MANipulation of Forest Ecosystems (EXMAN) project involves the imposition ofdrought through roofs in the forest subcanopy to five forest ecosystems in Europe. Initial results showed that this artificially imposed drought had no effects upon nitrification, but suggested that natural periods of drought could produce such pukes, as observed by Ulrich (1983).

In addition to affecting N mineralization and nitrification, drought can be expected to cause increased ionic concentrations in soil solutions, especially for conservative ions such as Cl^- and Na^+. Changes in the concentrations of other ions may be either buffered by soil chemical processes or controlled by mechanisms that are not sensitive to drought. In the cases of $H_2PO_4^-$ and SO_4^{2-}, for example, adsorption to Fe and Al hydrous oxides may mitigate concentration increases due to drought. In the case of HCO_3^-, concentrations are

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controlled by the partial pressure of CO, (pCO_2) in soil and soil solution pH, and could be affected either positively or negatively by drought. If drought causes reduced root and microbial respiration, pCO_2 could decrease. In addition, reduced effective soil CO, diffusivity with lower soil water concentrations would tend to result in lower pCO_2 (Wesseling, '1963; Johnson et al., 1994). On the other hand, drought may cause increased HCO_3^- concentrations by causing increased pH. The effects of drought on cations in soil solution should in theory be a function of changes in total ionic concentration. As noted by Reuss (1983), increased total ionic concentrations cause trivalent cations to increase disproportionately to divalent and monovalent cations (to the 3/2 and 3rd power, respectively) and divalent cations to increase as the square of monovalent cations.

To investigate the potential effects of changing precipitation on forest ecosystems, including nutrient cycling, the Throughfall Displacement Experiment (TDE) was established on Walker Branch Watershed, Tennessee in 1994. This experiment modified the amount of throughfail at -33 %, ambient (no change), and +33 % using a system of rain gutters and sprinklers. In this paper, we report the initial results of the treatment effects upon soil solution chemistry, compare those results to simulation output from the Nutrient Cycling Model (NuCM), and present a long-term forecast of the treatment effects from the NuCM model. In both the field experiment and the model simulations, the changes in water flux also cause proportional changes in ion flux to the system, and thus it may at first seem that soil solution concentrations could remain unchanged. However, in both cases, we expected to observe significant treatment effects on soil solution concentrations because the changes in throughfall or precipitation water flux should cause disproportionate changes in soil water flux. Luxmoore and Huff (1989) noted that, over a period of years, streamflow was much more closely related precipitation than was apparent evapotranspiration (ET; the difference between precipitation inputs and streamflow outputs). This suggests that ET was relatively constant and changes in precipitation caused disproportionately large changes in soil water flux and streamflow. Thus, we hypothesized that the drier treatments would cause: 1) disproportionate reductions in soil water flux, 2) increased total ionic concentrations in soil solution ,which would in turn cause 3) decreased SO_4^{2-}/Cl^- ratios, 4) decreased HCO_3^- concentrations, and 5) increased ratios of Al to (Ca^{2+} + Mg^{2+}) and of (Ca^{2+} + Mg^{2+}) to K^+.

2. Site and Methods

2.1. SITE DESCRIPTION

The throughfall displacement system for the experiment is located on the Walker Branch Watershed (35°58' N and 84" 17' W), a part of the U.S. Department of Energy's (DOE's) National Environmental Research Park near Oak Ridge, Tennessee (Johnson and Van Hook, 1989). Long-term mean annual precipitation is 1,358 mm and mean temperature is 14.2 "C. The acidic forest soils (pH 3.5 to 4.6) are Typic Paleudults (Fullerton series). Depth to bedrock at this location is approximately 30 m. The site was chosen because of its uniform slope, consistent soils, and a reasonably uniform distribution of vegetation. The site is dominated by *Quercus alba* L., *Quercus prinus* L. and *Acer rubrum* L., but it contains 16 other tree species (Hanson et *al.,* 1995). Stand basal area averages 20 to 25

m^2 ha“. The experimental area was located at the upper divide of the watershed so that lateral flow of water into the soils at the top of the plotswould not confound attempts to create a reduced soil water treatment. The site was also chosen to have a southern aspect so that the impacts of the reduced moisture treatment would be increased.

2.2. Experimental Design

The experimental design and its performance were described in detail by Hanson *et* al., (1995). Briefly, the manipulations of throughfall reaching the forest floor are made with a system designed to passively transfer precipitation from one experimental plot to another. There are three plots in the TDE; one wet, one dry and one ambient. Each 80 × 80 m plot is divided into 100 8 × 8 m subplots that serve as the locations for repetitive, nondestructive measurements of soil and plant characteristics. Throughfall is intercepted in about 2,000 subcanopy troughs (0.3 × 5 m) suspended above the forest floor of the dry plot (-33 % of the ground area is covered). The intercepted throughfall is then transferred by gravity flow across an ambient plot and is distributed onto the wet treatment plot through paired drip holes spaced approximately 1 m apart. The troughs are arranged in 2 1 rows of 80 to 90 troughs. Reductions in soil moisture anticipated from the experimental removal of 33 % of the throughfall will be comparable to the driest growing season of the 1980’s drought (Cook *et* al., 1988), which resulted in sapling mortality and reduced growth of some vegetation (Jones *et al.,* 1993).

2.3. Soil Solution Collections

Soil solutions were collected with ceramic cup tension lysimeters (Soil Moisture Equipment Corp., Santa Barbara, California). The lysimeters were installed prior to treatment in a 3 × 3 array in each subwatershed at a spacing of 7.9 m. Prior to collection of samples, tensions of 40 kPa were established in each lysimeter. Soil water content (%, v/v) also was measured in each subwatershed with a time domain reflectometer. Data from those measurements are not used in this analysis; the reader is referred to Hanson *et al.* (1995) for details of methodology and results.

3. The NuCM Model

The NuCM model has been described in detail elsewhere (Liu *et* al., 199 1; Johnson *et al.,* 1993), and only a few relevant details are repeated. NuCM depicts nutrient cycling at a stand level, where the ecosystem is represented as a series of vegetation and soil components. The model provides for one generic conifer and one generic deciduous species of specified biomass and nutrient concentration (foliage, branch, bole, roots). The model also. provides for an overstory that can be divided into canopy, bole, and roots. Tree growth in the model is a function of user-defined stand developmental stage and the availability of nutrients and moisture. The soil includes multiple layers (up to 10), and each layer can have different physical and chemical characteristics. The model routes precipitation through the canopy and soil layers, and simulates evapotranspiration, deep seepage, and lateral flow. The movement of water through the system is simulated using the continuity equation, Darcy's equation for permeable media flow, and Manning's equation for free surface flow. Percolation occurs between layers as a function of layer permeabilities and differences in moisture content. In these simulations, meteorological data from the period January 1992 through December 1994 were used to generate hydrologic fluxes. These input files were repeated to produce longer-term simulations. Nutrient pools associated with soil solution, the ion exchange complex, minerals, and soil organic matter are all tracked explicitly. The processes that govern interactions among these pools include user-specified rates for decay, nitritication, anion adsorption, cation exchange and mineral weathering.

The model simulates the noncompetitive adsorption of sulfate, phosphate, and organic acids. Sulfate adsorption can be simulated in NuCM using either linear or Langmuir adsorption isotherms. The Langmuir isotherm was used in these simulations. Phosphate adsorption in the model is represented by a linear isotherm. Cation exchange is represented by the Gapon equation. Mineral weathering reactions in the model use rate expressions that depend upon the mass of mineral present and solution-phase H^+ concentration raised to a fractional power.

4. Field Results

4.1. Pre-treatment Soil Solutions

Unfortunately, there were some pre-treatment differences in soil solution concentrations that complicate interpretations ofpost-treatment effects. Table I shows some soil solution concentration data from the 70 cm depth lysimeters prior to treatment in May and December, 1992 (nine replicates per treatment and date). There were no pre-treatment differences in pH on either date, but there were statistically significant (ANOVA, $p < 0.05$) pre-treatment differences in Ca^{2+}, K^+, Mg^{2+}, and Na^+ concentrations on 13 May and differences in SO_4^{2-} concentration on both 13 May and 12 December. None of the differences in cation concentration were significant on the 12 December date. The direction of these differences in base cations and SO_4^{2-} was indeed unfortunate: the site fated for the Dry treatment had higher concentrations of all four base cations than the sites fated for either the Ambient or Wet treatments. There were also statistically significant pre-treatment differences in Cl concentrations and in SO_4^{2-}/Cl^- ratio between the Wet and Ambient treatments on 12 December (but not between the Ambient and Dry treatments; Student's t-test). In these cases, however, the pre-treatment differences were in the opposite direction of hypothesized post-treatment changes (lower pre-treatment Cl^- concentrations and higher SO_4^{2-}/Cl^- ratios in the Ambient than in the Wet treatment). Nitrate and NH_4^+ concentrations in soil solution were very low ($< 2\ \mu mol_c\ L^{-1}$) and there were no statistically significant pre-treatment differences. There were no significant differences in Ca^{2+}/K^+ or Mg^{2+}/K^+ ratios; Al concentrations were near trace levels.

4.2. Post-treatment Soil Solutions

The Dry treatment had consistently higher electrical conductivity, SO_4^{2-}, Cl^-, K^+, Ca^{2+}, Mg^{2+}, and Na^+ concentrations than either the Ambient or Wet treatments within the fourth year oftreatment (Figure 1). As in the pre-treatment collections, there were no treatment effects on **pH,** NH,‘, NO,‘, **Ca^{2+}/K^{+} or Mg^{2+}/K^{+} ratios,** and Al concentrations were near trace levels (not shown). In the cases of all ions except **Cl^-,** these differences were present prior to treatment and therefore cannot necessarily be attributed to the treatments. In the case of **Cl^-,** however, the pre-treatment effects were in the opposite direction **(Cl^-** was lower in the Dry treatment site), and therefore it can be concluded that there was a treatment effect. Also, the post-treatment decreases in **SO_4^{2-}/Cl^-** ratios in the Dry treatment can be considered a treatment effect because pre-treatment differences between the Ambient and Dry treatments were not significant.

TABLE I

Soil solution concentrations ($\mu mol_c\ L^{-1}$; means ± standard errors, n = 9) at two dates prior to treatment (Wet = site to receive +33 % throughfall input; Ambient = no treatment; Dry = site to receive -33 % throughfall).

	Treatment		
	Wet	Ambient	Dry
13 May 1992			
pH	5.9 ± 0.2	6.2 ± 0.1	5.9 ± 0.2
Ca^{2+}	116 ± 17	191 ± 32	193 ± 20
K^+	40 ± 10	45 ± 7	57 ± 9
Mg^2	57 ± 8	77 ± 5	94 ± 6
Na^+	35 ± 2	35 ± 1	42 ± 1
Cl	31 ± 2	28 ± 4	28 ± 3
SO_4^{2-}	360 ± 41	457 ± 50	552 ± 47
SO_4^{2-}/Cl	3.9 ± 0.5	5.8 ± 1.0	6.8 ± 1.1
12 Dec. 1992			
pH	5.4a0.1	5.5 ± 0.1	5.4 ± 0.1
Ca^{2+}	138 ± 12	166 ± 25	169 ± 16
K^+	53 ± 9	42 ± 8	52 ± 10
Mg^{2+}	59 ± 8	60 ± 8	79 ± 9
Na^+	35 ± 9	26 ± 2	33 ± 4
Cl	40 ± 5	24 ± 6	30 ± 6
SO_4^{2-}	387 ± 23	433 ± 38	497 ± 26
SO_4^{2-}/Cl	3.9 ± 0.9	8.2 ± 1.7	7.5 ± 1.5

5. Model Simulations

5.1. Simulated Water Fluxes

Simulated hydrologic fluxes using the NuCM and PROPSER (Luxmoore *et al.,* 1978) models are compared for calendar years 1992 and 1996 in Table II. Simulations for the two models differ most with respect to evapotranspiration (ET) and overland flow (OF).

NuCM simulations suggest that ET increases with water input (from 5 1 to 8 1 cm, Dry to Wet) whereas PROSPER suggests that ET is nearly constant. NuCM simulations indicate virtually no overland flow, whereas PROSPER shows a moderate amount of flow that increases with water input (from 1 to 12 cm, Dry to Wet). In the case of soil leaching (SWF), however, the parameter of most interest here, the models produce remarkably similar results. In both cases, SWF increases by approximately 30 cm with each increase in water input. However, in a relative sense, SWF differs more from Dry to Ambient (+74 to 80 %) than from Ambient to Wet (+45 to +47 %), and thus Hypothesis 1 was supported by the simulations.

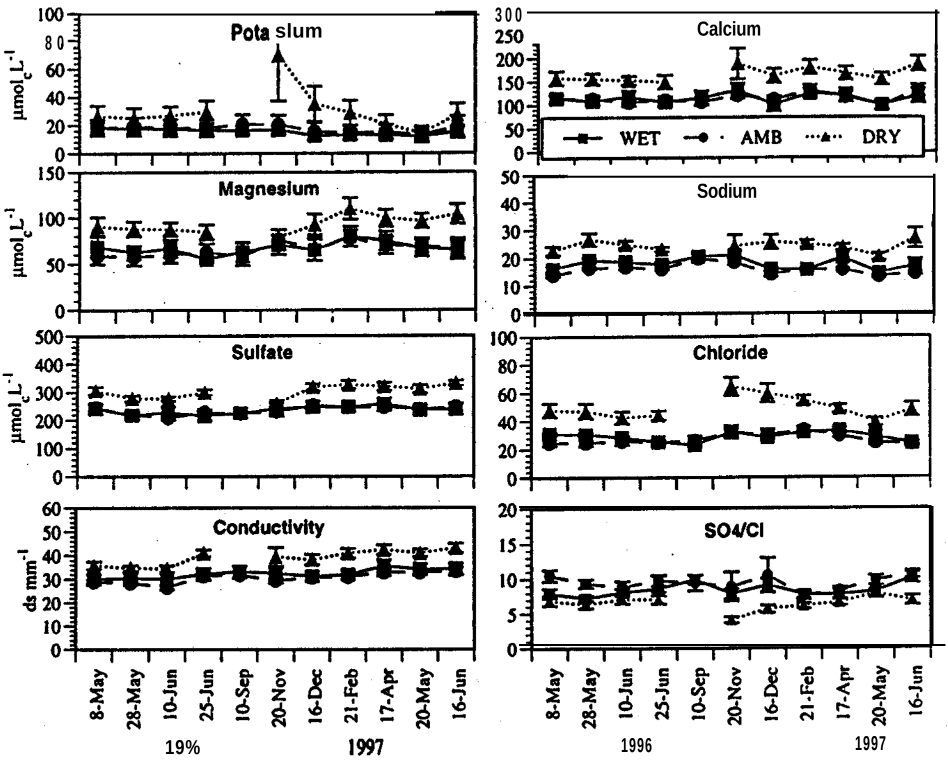

Fig. 1. Concentrations of K^+, Ca^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, Cl^-, and total cations, and SO_4^{2-}/Cl^- ratio in Bt2 horizon (70 cm) soil solutions from the Throughfall Displacement Experiment (Wet = +33 % throughfall; Ambient = no treatment; Dry = -33 % throughfall).

5.2. Simulated Soil Solutions

Simulated soil solution concentrations of total cations, SO_4^{2-}, Cl^-, SO_4^{2-}/Cl^- ratios, K^+, Ca^{2+}, Mg^{2+}, and Na^+ over a four year period are shown in Figure 2. The simulations matched the patterns during year four of treatment fairly well in some cases and poorly in others. In the cases of simulated total cations vs. measured conductivity, SO_4^{2-}, Ca^{2+}, Mg^{2+}, and

Na^+, the simulated patterns during year four followed the patterns in the field to some extent: seasonal variations were minimal and the differences between the Wet and Ambient treatments was less than those between the Dry and Ambient treatments. In the cases of Cl^- and K^+, however, the simulated patterns in year four differed substantially from those in the field. Unlike the field data, simulated Cl‘ varied seasonally by a factor of three. In the case of K^+, the simulations indicated very little seasonal variation and very minor treatment effects. In the field, there was a large seasonal variation in K^+ in the Dry treatment and a very large treatment effect during peak concentrations. In contrast to the field results, the NuCM simulations showed only a very slight response of SO_4^{2-}/Cl^- ratios to treatments in the fourth year of treatment. There were larger but inconsistent responses of SO_4^{2-}/Cl^- ratios to treatments in years 1-3 of the simulation.

TABLE II

Simulated water fluxes using the NuCM and PROSPER models (cm). Average of two years (1993 and 1994). (Wet = +33 % precipitation; Ambient = no treatment; Dry = -33 % precipitation .

	Treatment		
	Dry	Ambient	Wet
NuCM			
Precipitation	94	139	186
Evapotranspiration	51	67	81
Overland Flow	<1	<1	<1
Soil Water Flux	42	73	107
PROSPER			
Precipitation	99	141	183
Evapotranspiration	60	56	63
Lateral Flow	2	6	12
Soil Water Flux	41	74	107

5.3. Long-term Simulations of Nutrient Pools

Increasing water input had only a minor effect (4 to 7 % increase) upon simulated biomass and vegetation nutrient contents after 30 years (Table III). Increasing water had a somewhat greater effect upon forest floor nutrient content (from a 14 % increase for P to a 25 % increase for K). The effect of increasing water upon soil exchangeable pools differed substantially among nutrients: negligible for N, 1% decrease for SO_4^{2-}, 28 % decrease for P, 62 % decrease for Ca^{2+}, 49 % decrease for K^+, and 35 % decrease for Mg^{2+}. Changes in soil total pools during the simulation were negligible (not shown). None of the decreases in soil exchangeable pools caused a nutrient deficiency to develop during the simulation.

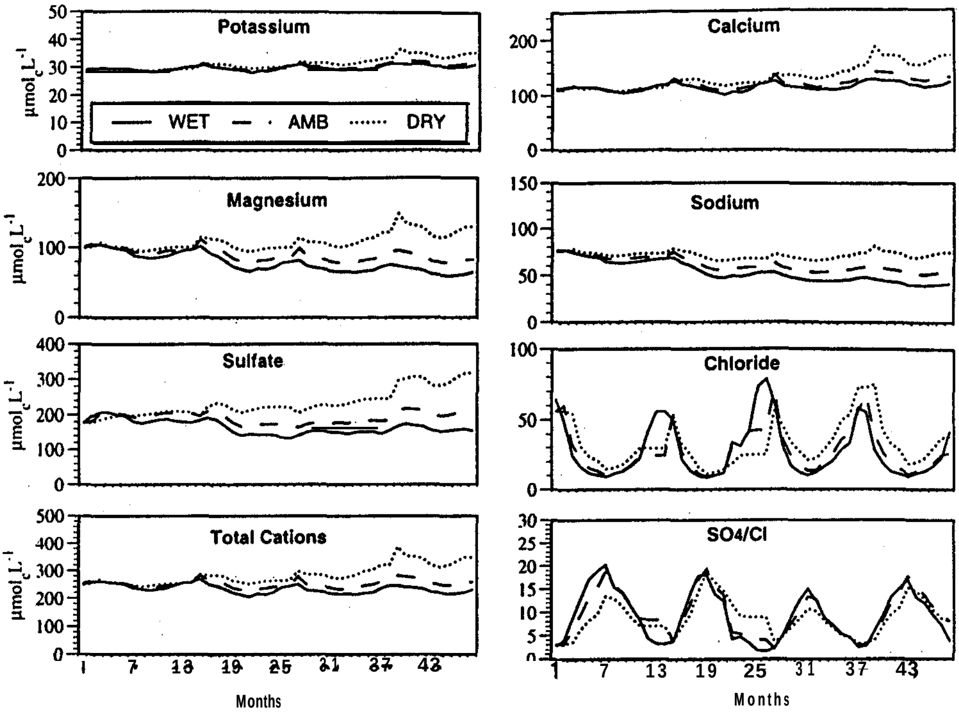

Fig. 2: Simulated concentrations of total cations, SO_4^{2-}, Cl^-, SO_4^{2-}/Cl^- ratios, K^+, Ca^{2+}, Mg^{2+}, and Na^+ in Bt2 horizon (70 *cm)* soil solutions from the Throughfall Displacement Experiment. (Wet = +33 % throughfall; Ambient = no treatment; Dry = -33 % throughfall).

6. Discussion

Hypothesis 1 (reduced water would lead to disproportionate reduction in soil water flux) was supported by simulation results form both the PROSPER and NuCM models. No field data are available to verify these results, but treatment effects on soil water content have been noted throughout the growing season except during the drought of 1995 (Hanson et al., 1995). Hypothesis 2 (reduced water would result in increased total ionic concentrations) was supported in part by the Cl^- results. The post-treatment increases in Cl^- in the Dry treatment clearly were due to the treatment rather than pre-treatment site bias and suggest that soil solution concentrations other ions also were affected by treatments even though pre-treatment differences existed. The pre-treatment differences in Cl' between the Wet and Ambient sites (higher in the Wet site) disappeared in the post-treatment collections, also suggesting treatment effects on Cl^- (and perhaps also on total ionic strength).

TABLE III

Simulated ecosystem nutrient contents (kmol ha") (Wet = site to receive +33 % throughfall input; Ambient = no treatment: Dry = site to receive -33 % throughfall).

	Initial	After 30 years		
		Wet	Ambient	Dry
Biomass	19.30	24.91	24.66	23.97
Nitrogen				
Vegetation	38.76	48.56	47.85	46.42
Forest Floor	II.59	19.84	18.84	17.59
Soil, Exch.	<0.01	co.0 I	<0.01	co.01
Sufur				
Vegetation	2.57	3.37	3.30	3
Forest Floor	1.41	3.69	3.44	3.13
Soil, Exch.	12.37	13.07	13.12	13.22
Phosphorus				
Vegetation	1.62	2.08	2.05	I.99
Forest Floor	0.29	0.58	0.55	0.5 I
Soil, Exch.	0.44	0.26	0.29	0.36
Calcium				
Vegetation	25.92	33.10	32.69	31.76
Forest Floor	3.21	10.38	9.65	8.82
Soil, Exch.	22.90	2.33	3.27	6.01
Potassium				
Vegetation	8.95	II.13	10.97	IO.61
Forest Floor	2.01	4.29	3.87	3.43
Soil, Exch.	27.65	10.01	14.61	19.63
Magnesium				
Vegetation	4.30	5.52	5.43	5.27
Forest Floor	0.77	2.59	2.40	2.20
Soil. Exch.	4.37	0.70	0.77	I.07

Hypothesis 3 (reduced water would cause decreased SO_4^{2-}/Cl^- ratios) also was supported in part by theresults of the field collections. Soil solution SO_4^{2-}/Cl^- ratios were reduced in the Dry compared to the Ambient treatment after treatment whereas there were no significant differences before treatment. The situation between the Wet and Ambient sites for SO_4^{2-}/Cl^- ratios is less clear. The pre-treatment differences in SO_4^{2-}/Cl^- ratios between the Wet and the Ambient sites (Wet was lower) persisted only in the Spring samples of the post-treatment collections. Hypothesis 4 (reduced water would cause decreased HCO_3^- concentrations) was not supported by the limited data on hand. However, the data are not adequate to refute this hypothesis because no pre-treatment data were available, and post-treatment HCO,' concentrations were often at trace levels. Hypothesis 5 [reduced water would result in increased ratios of Al to $(Ca^{2+} + Mg^{2+})$ and of $(Ca^{2+} + Mg^{2+})$ to K'] was not supported by the results of the field collections.

The NuCM simulation results offer a few additional insights into factors that might be affecting field responses and additional factors that might be desirable in the model. The simulation results suggest that the differences in concentration between the Dry and Ambient treatments are greater than those between the Wet and Ambient sites because of the greater relative effect on soil water flux in the former than in the latter (Table II; Figure 2). The failure of the NuCM simulations to match observed patterns in soil solution Cl' suggests that there is some buffering of Cl^- in the field (e.g., adsorption; Johnson and Cole, 1977) that is not accounted for in the model. On the other hand, the failure of NuCM to simulate the observed seasonal variations of K^+ in the field may reflect too much emphasis on buffering by cation exchange. For the purposes of comparison with field data, NuCM results from only the deepest horizon (Bt2) are shown in Figure 2. The simulations also produced output for the surface horizons, and these are shown for K^+ in Figure 3. The NuCM simulations showed considerable seasonal variations and treatment effects in soil solution K^+ in surface horizons, but these variations were buffered by exchange processes in the Bw2 horizon. In the field, the appearance of seasonal variations in the Bw2 horizons may have been due to macropore flow (e.g., Luxmoore *et al.*, 1981), which is not accounted for in the NuCM model.

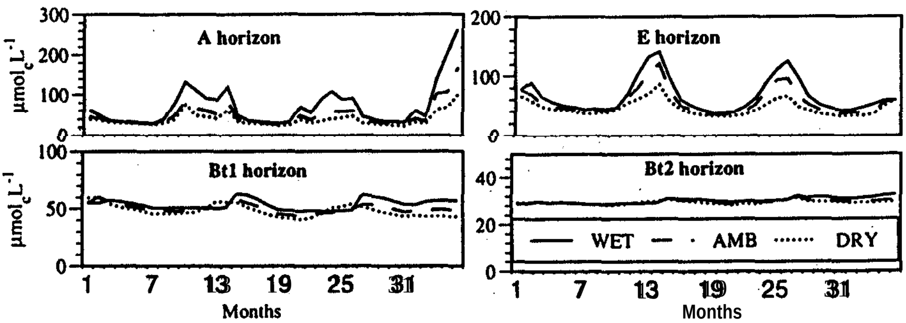

Fig. 3. Simulated concentrations of K^+ in A, E, Bt1 and Bt2 horizon soil solutions from the Throughfall Displacement Experiment (Wet = +33 % throughfall; Ambient = no treatment; Dry = -33 % throughfall.)

There is no way to either verify or disprove the long-term simulation results from the NuCM model. However, it is intuitively obvious that changes in water flux could cause substantial changes in the rate of K cycling because of the fact that so much K is cycled via foliar leaching. Thus, it is to be expected that changing water would have a large effect on forest floor and soil exchangeable K^+ pools (Table III). It is also intuitively obvious that nearly two-fold changes in the soil water flux and, consequently, in the rate of soil leaching would cause significant reductions in adsorbed P exchangeable Ca^{2+} and Mg^{2+} pools. The lack of change in soil SO_4^{2-} pools in the simulations pools suggests that the system is near steady-state with respect to SO_4^{2-} adsorption.

7. Conclusions

Based upon the literature and theoretical considerations, we hypothesized reduced water inputs in the Throughfall Displacement Experiment would cause: 1) disproportionate reductions in soil water flux, 2) increased total ionic concentrations in soil solution, which would in turn cause 3) decreased SO_4^{2-}/Cl^- ratios, 4) decreased HCO_3^- concentrations, and 5) increased ratios of Al to $(Ca^{2+} + Mg^{2+})$ and of $(Ca^{2+} + Mg^{2+})$ to K'. Hypothesis 1 was supported by simulation results. Hypotheses 2 and 3 were supported in part by field results, although interpretation of these was complicated by pre-treatment biases. Hypotheses 4 and 5 were not supported by the field results. Comparisons of field data and NuCM model simulations were favorable for most ions except Cl^- and K^+. Disparities between simulation outputs and field results for these ions suggest that Cl^- adsorption may be occurring in the field (not accounted for in the model) and that macropore flow (not accounted for in the model) may allow seasonal pulses of K'and other ions to penetrate the soil profile. Long-term simulations with the NuCM model suggest that reducing water inputs will slow the rate of soil acidification and P loss, but would not materially affect growth or ecosystem N status.

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